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Transmission and reflection from a free carrier front in a silicon slow light waveguide

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Abstract: Optical transition with changes of frequency and wave vector can be induced by optically generated free carrier fronts that move along a slow light photonic crystal waveguide and interact with a co-propagating signal wave. With the flexibility in dispersion designs of these waveguides, a variety of indirect photonic transitions can be envisaged. The signal wave transmitted through the front experience an inter-band transition, while the wave reflected from the front – an intra-band transition. Theory and experimental results are presented.

OCIS codes: (190.0190) Nonlinear optics; (130.0130) Integrated optics.

1. Introduction

Dynamic manipulation of light has received considerable attention in recent years [1–4]. The process of an optical signal undergoing a transition between two modes of a photonic structure is referred to as a photonic transition [5,6]. Photonic transitions can be direct, if the optical signal experiences a shift in frequency but not in wave vector, or indirect, if both frequency and wave vector of the signal are changed. While, by only introducing spatial perturbations in the structure, the signal wave vector will be altered without frequency shift. In case of direct transition, the magnitude of the resulting optical frequency shift is limited to the maximum induced instantaneous refractive index change. Direct transitions have been shown for light travelling in a millimeter-long semiconductor slab [7] and for light confined in microphotonic resonators [4,8,9] as well as in photonic crystal (PhC) waveguides [10,11]. The required fast change of refractive index is achieved by generating free carriers in silicon, which leads to a refractive index change via the carrier plasma dispersion effect [12].

On the other hand, indirect photonic transitions imply both a change of frequency and wave vector of the optical signal [6,13]. The indirect photonic transitions between modes that belong to different photonic bands are called indirect *inter-band* transitions [14,15], while transitions to the same band are called indirect *intra-band* transitions [16].

We have shown, that the time and space dependent phase of a signal co- or counter-propagating with a moving front is continuous at the position of the front, independently of the reference frame of the observer, e.g., invariant with respect to any Lorentz-transformation. This way we could show that the ratio of the frequency change $\Delta\omega$ and wave vector change Δk induced by the interaction with the moving front is identical to the velocity at which the front propagates, e.g., the group velocity of the pump. Hence, the phase continuity line defines all possible states of the signal which satisfy the continuous phase at the moving front; therefore the front can only transform the signal to states which lie on that line. As a result, the induced frequency and wave vector changes are determined by the dispersion curve of the system, the propagation velocity of the front and the initial position of the signal wave vector and frequency in the dispersion band.

In the next sections we will show, that with the flexibility in dispersion designs of PhC waveguides [17,18], a variety of indirect transitions can be envisaged. First we will discuss the situation when a signal wave ahead of a faster index front is overtaken by it and its final state after the interaction will lie on the perturbed dispersion curve, i.e. inter-band indirect transition. Then we will demonstrate a special situation when the signal wave ahead of a front cannot find states on the band of the switched PhC behind the front and hence remains in the initial band, i.e. an intra-band transition takes place.

2. Inter-band indirect photonic transition

The indirect photonic transitions shown here rely on the interaction of an optical signal with a moving refractive index front via the carrier-plasma dispersion effect [14,15]. After injection of a high power pump pulse into a PhC waveguide, the pulse modifies the optical properties of the waveguide by generating free carriers via two photon absorption (TPA). In the switched zone, the refractive index of silicon, n_{si}, reduces by a quantity Δn_{FC} that is proportional to the free carrier density N_{FC}, which in turn changes and blue shifts the dispersion curve.

To implement indirect transitions, we employed single line defect PhC waveguide fabricated on a Silicon-on-Insulator substrate with slab height of 220 nm. The lattice constant of the PhC is 404 nm and the air-hole diameter is 230 nm [14]. Further, the first row of holes directly adjacent to the waveguide has been shifted 50 nm away from the waveguide center [18]. Figure 1(a) shows the measured group index of the TE-mode of the slow light PhC waveguide. In order to induce an inter-band indirect transition, we chose the wavelengths and group indices of pump pulse and signal wave as indicated by orange and red dots, respectively. This means that the group velocity of pump pulse is faster than the velocity of the signal wave, and therefore will overtake it. The basic concept to induce this transition is schematically shown in Fig. 1(b). The solid curve represents the dispersion band of waveguide mode in the ground state (with refractive index n_{si}), while the dashed curve indicates the switched state with refractive index $n_{\mathrm{si}} + \Delta n_{\mathrm{FC}}$. The orange line represents the phase continuity line with a slope equal to the group velocity of the pump pulse. At the input of the structure, the signal wave travels in a waveguide with silicon refractive index of n_{si}, and is represented by a point (ω_1, k_1) lying on the corresponding dispersion curve. Hence, the final state of the signal (ω_2, k_2) after interaction with the moving front is determined graphically from the crossing point of the phase continuity line and the upper dashed dispersion curve. This means that the signal pulse is overtaken by the front and travels in a waveguide with silicon refractive index of $n_{\mathrm{si}} + \Delta n_{\mathrm{FC}}$ with higher frequency. Figure 1(c) shows a schematic illustration of this process at two different times.

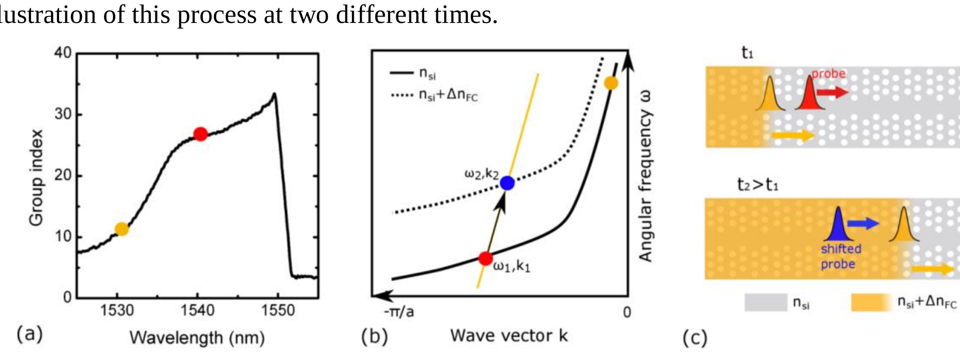

Figure 1: (a) Measured group index of the engineered and fabricated slow light silicon PhC waveguide. Dots indicate the locations of the input wavelengths of signal wave (red dot) and pump pulse (orange dot). (b) Schematic representation of an inter-band indirect photonic transition. The solid curve represents the dispersion band of waveguide mode in the ground state (with refractive index n_{si}), while the dashed curve indicates the switched state with refractive index $n_{\mathrm{si}} + \Delta n_{\mathrm{FC}}$. The orange line represents the phase continuity line with a slope equal to the group velocity of the pump pulse. Blue dot indicates the expected output wavelength of the shifted signal wave after inter-band transition took place. (c) Schematic of the experiment. A pump pulse generates free carriers in the silicon by TPA and, consequently, induces a change of refractive index which propagates with the velocity of the pump pulse. The region with the orange color gradient corresponds to the rising edge of the front. The orange arrow indicates the velocity of the pump pulse, while red and blue arrows indicate the velocities of the signal at different times.

3. Intra-band indirect photonic transition

Now, we are interested in the particular situation where the signal wave ahead of a front cannot find states on the band of the switched PhC behind the front. This can happen when the phase continuity line does not cut through the band of the perturbed PhC. Thus, the state of the signal wave, after interacting with the moving front, must remain in the initial band which means that an intra-band transition takes place. This intra-band transition manifests itself as a forward reflection from the front. This transition can be achieved by setting the pump pulses at the knee of the solid band in Fig. 2(b) at the frequency where group velocity corresponds to the slope of the phase continuity line. However, by choosing the pump pulse to lie at the knee of the dispersion band, has some experimental drawbacks. Firstly, due to the high intensity of the pump pulse and its center frequency close to that of the signal wave, it is difficult to detect the shifted signal after interaction. Secondly, it is also challenging to distinguish the intra-band transition from third order nonlinear processes such as four wave mixing (FWM) which would cause spectrally similar signals. Thus, the pump should be positioned at some other frequency where the group velocity is the same as at the knee of the dispersion band.

However, PhC waveguides overcome these problems due to their inherent flexibility in dispersion design [17,18]. Slow light PhC waveguides can also be engineered to obtain a dispersion relation with equal group velocities at three different frequencies [18]. Therefore, it can be used to excite pump pulses with the required group velocity at a frequency distant from the initial and final frequencies of the signal. Thus to implement intra-band transitions, we used a single line defect PhC waveguide consisting of a hexagonal lattice of air holes in silicon. The lattice constant of the PhC is 404 nm and the air-holes diameter is 240 nm. The first row of holes directly adjacent to the waveguide has been shifted 50 nm away from the waveguide center as well [18]. Figure 2(a) shows the measured group index of the TE-mode of the over-engineered PhC waveguide. Equal group velocities at three different frequencies are illustrated by A, B, and C points. Figure 2(b) presents a schematic representation of the intra-band indirect photonic transition, which can be obtained by setting the signal wave at a frequency close to the knee of the solid line. The knee of the solid line represents point A in Fig. 2(a), while the orange dot represents point C. In such configuration, the signal wave is initially propagating slower than the approaching pump pulse. The final state of the signal (ω_2, k_2) after interaction with the front is determined graphically from the crossing point of the phase continuity line and the solid band. Dashed blue dot corresponds to inter-band transition at insufficient band shift. Fig. 2(c) shows a schematic illustration of intra-band transition process. The fascinating fact is that a signal wave initially propagating slower than the approaching pump pulse, upon interaction with the moving front, which is dragged by the faster pump pulse, is accelerated and finally escapes from the moving front in the forward direction.

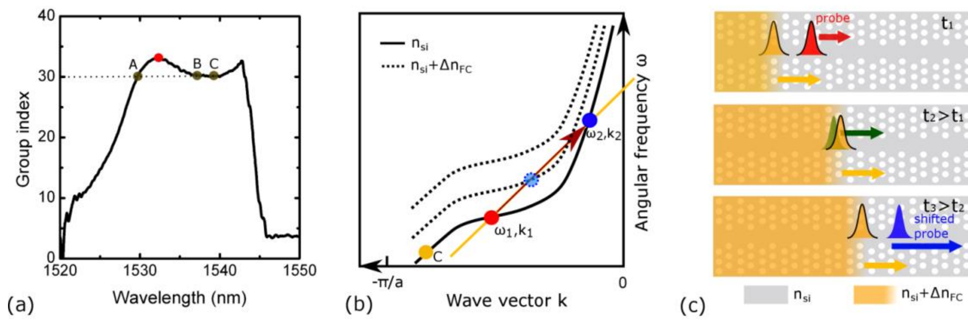

Figure 2: (a) Measured group index of the over-engineered slow light silicon PhC waveguide. Here, the dispersion relation shows equal group velocities at three different frequencies A, B and C. (b) Schematic representation of an intra-band indirect photonic transition, obtained by setting the signal wave at a frequency close to the knee of the solid line and the pump pulses corresponding to point C in (a). The inter-band and intra-band photonic transitions of the input signal caused by insufficient (dashed blue dot) and by sufficient (solid blue dots) values of Δn, respectively. (c) Schematic of the experiment. The orange arrow indicates the velocity of the pump pulse, while red, green, and blue arrows indicate the velocities of the signal at different times, respectively.

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